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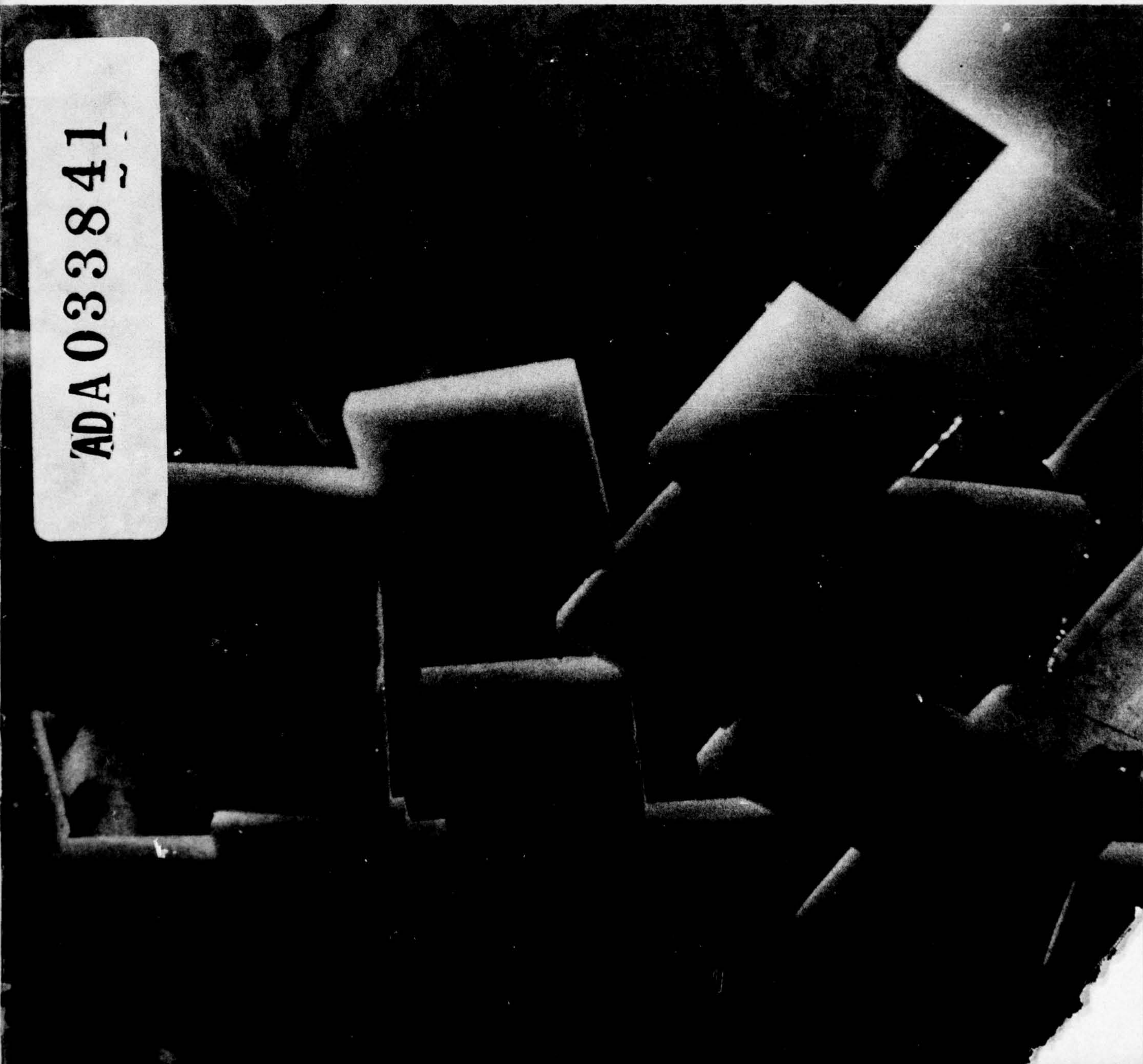

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Cover: Simulated ice blocks arching across boom opening. (Photograph by Darryl Calkins.)

CRREL Report 76-42

Arching of model ice floes: Effect of mixture variation on two block sizes

Darryl J. Calkins and George D. Ashton

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A study of arching of mixed, square fragmented ice floes at an opening in an ice boom is documented, using results from a model study in which two sizes of plastic blocks represented real ice. A power function, relating the upstream ice concentration to the ratio of a characteristic block dimension to the gap opening, is found adequate to distinguish between arching and nonarching events for block mixtures of two component sizes. It is demonstrated that when the respective total areas of the two block components are nearly equal, a minimum ice concentration initiates an arch across the opening. As the mixture of two sizes of blocks approaches a uniform (one-sized) mixture, a higher concentration of ice is needed to initiate the arch. When the ratio of the block dimension to the gap

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opening is equal to or less than 0.10, arching of the fragmented ice is not possible, even when the upstream ice discharge exceeds the maximum discharge of ice through a gap opening. The distribution of fragmented ice areas is an important parameter in establishing the minimum size of opening at which an ice boom will retain its arching capability.

PREFACE

This report was prepared by Darryl J. Calkins, Research Hydraulic Engineer, Applied Research Branch, Experimental Engineering Division, and by Dr. George D. Ashton, Chief, Snow and Ice Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. The experimental work in the flume was conducted by James Morse, Electronics Technician of the Technical Services Division. The research was funded by Corps of Engineers Civil Works Project 31332. Kevin Carey of CRREL technically reviewed the manuscript.

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SUMMARY

Mixtures of two sizes of square model ice floes were examined for their arching characteristics at an opening of an ice boom, subject to the condition that surface water velocities were slower than the critical velocity for underturning or submerging individual ice pieces. Polyethylene blocks were used as the model ice and experiments were conducted in a laboratory flume (see cover photograph).

The results of this study are clearly applicable to navigation in winter environments. The arching of ice at an opening in a surface barrier is similar to that at gapped ice booms, such as those which are used for winter navigation.

The arching of model ice blocks could be distinguished on the basis of the surface ice concentration, ice block dimensions, proportionment of ice block sizes, and width of the gap opening. A power function is given which separates the arching and nonarching events. A mixture of ice blocks (of more than one size) arches much more easily than ice blocks of all the same size. The same conclusion is seen in arching of materials from bins and hoppers.

ARCHING OF MODEL ICE FLOES: EFFECT OF MIXTURE VARIATION FOR TWO BLOCK SIZES

Darryl J. Calkins
George D. Ashton

INTRODUCTION AND BACKGROUND

The study described in this report investigated the conditions of arching at a simulated ice boom opening with two sizes of low-density, translucent polyethylene model ice floes of 0.92 specific gravity. The two square block sizes, with side dimensions a of 37 mm and 74 mm and with 6.4-mm thickness, were mixed in various combinations of $n_2 : n_1$ (the ratio of large to small pieces) for several experiments to establish arching and nonarching conditions over a range of ice discharges Q_i and boom gap openings b (Fig. 1).

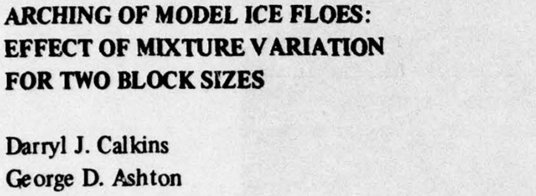

Figure 1. Plan of experimental setup where B *is the width of the upstream channel,* b *the gap width,* a *the block size,* V_s *the surface velocity, and* Q_1 *the ice discharge.*

A previous study on arching of model fragmented ice covers was conducted by Calkins and Ashton[3] at an opening in a simulated ice boom. The model ice floes were similar to those used in this study. Two sizes (37-mm and 74-mm square) were used separately in one series of experiments and collectively in another. The main result of this study was a relationship that discriminated nonarching events from the arching events for uniform (single size) blocks. The few experiments conducted using a combination of large and small blocks suggested that arching of these fragmented floes would be enhanced when the distribution was other than uniform, i.e. when there was a mixture of blocks of two sizes.

Another study on arching of ice covers has been presented by Boulanger et al.[1] but with a limited set of data. These experiments were conducted with a physical model of the entrance to the Beauharnois Power Canal (in Canada), where an ice boom with a gap opening has been proposed. Sizes of their model ice pieces were not given, but the prototype ice floes mentioned were 11×11×1 m and 6×6×0.5 m. Since their horizontal model scale was 1/600, model sizes would be approximately 18-mm and 10-mm square with thicknesses of 1.67 and 0.84 mm, respectively.

The physical model made by Boulanger et al. allowed them to maintain a long accumulation of ice upstream of the opening. Their results indicated that arching is possible at lower block size to gap ratios (a/b) than was inferred by Calkins and Ashton.[3] Boulanger et al.[1] also recorded the time necessary for arching to occur. Generally speaking, as a/b approached 0.05, the time necessary for arching increased tenfold when compared to cases of $a/b \simeq 0.17$.

Model studies similar to those performed by Calkins and Ashton[3] have been conducted at the University of Iowa by Tatinclaux et al.[5] and have confirmed many of the results of the former study. An important matter also investigated by Tatinclaux et al. is whether plastic as a model ice is a proper substitute material for real ice. To date parallel experiments using real ice have been run, with no noticeable differences for the smaller floes, but with a significant difference for the large ice pieces (74 mm). Definite explanations for the differences are not as yet established, but the surface tension effect for small thickness blocks may be important.

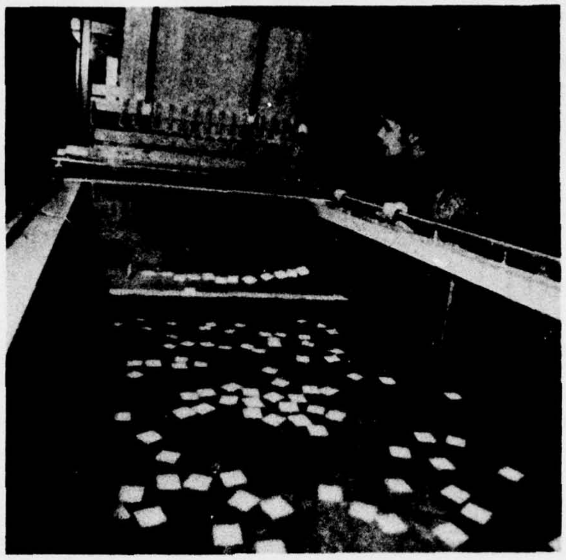

Figure 2. View of ice feeder.

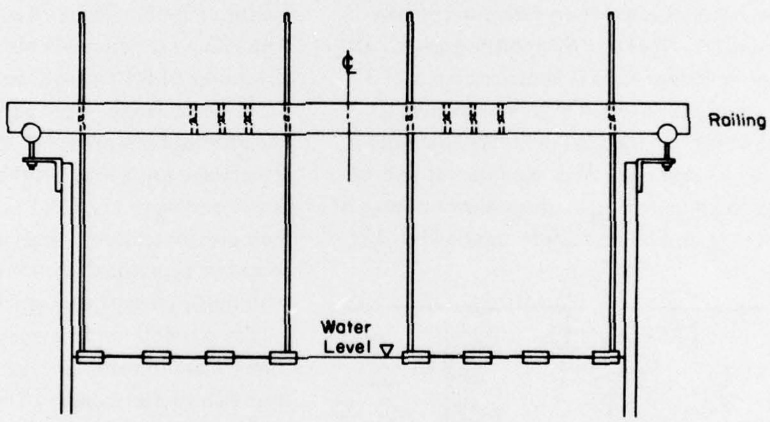

Figure 3. Cross section of surface barrier.

FACILITIES

The tests reported here were conducted in the CRREL hydraulic flume facility with a 0.92-x 0.92-m cross section, a total length of 7.3 m and a 0- to 0.3-m^3/s variable speed pumping capacity.[2] The simulated ice was low density, translucent and white polyethylene, cut on a band saw into 37-mm and 74-mm-square pieces from large 1.2-x 2.4-m sheets obtained from a local plastics distributor. The material had a specific gravity of approximately 0.92.

Model ice was discharged into the flume with a specially designed feed system which could accept various block dimensions (Fig. 2). The device was mounted over the flume on rail supports at the upstream end of the flume. The rate of block discharge could be controlled by the block feeder. The ice boom was simulated by wooden blocks (25x 25x 76 mm) strung on a nylon line with a 25-mm space between blocks, and with vertical supports at the gap opening (Fig. 3).

OBJECTIVE

The study by Calkins and Ashton[3] suggested that arching of ice floes would occur at lower rates of ice discharge for a given opening in an ice boom if the

model ice pieces were other than uniform, i.e. if more than one size of model ice were present. The present investigation used the two block sizes (37 mm and 74 mm square) in various combinations to evaluate the effect of block size distribution on the occurrence of ice arching at an opening in an ice boom.

DESIGN OF EXPERIMENTS

The distribution ratios of large blocks to small blocks were 1:1, 1:2.3, 1:4, 1:6 and 1:9. Experiments were conducted for each distribution over a range of gap openings from 0.16-0.45 m. The occurrence or nonoccurrence of arching was recorded for each run and gap opening, as were the ice discharge Q_i and surface velocity V_s. Time-lapse photography recorded all events; a 16-mm movie camera was mounted over the flume above the ice boom and operated at one frame per second.

The surface velocities were measured by timing the blocks over a 2-m length of the flume and were checked at point locations with a minicurrent meter. The surface velocities were sufficiently low that no underturning or submergence of blocks occurred. An arch was considered stable when no ice discharged through the opening and the subsequent arch upstream released no ice pieces for a period of 30-45 s. Even when an arch formed early in the experiment, the entire supply of blocks was generally released each time, unless it was obvious that the arch was stable (as occurred frequently for small gap widths and high ice discharges). The upstream surface ice discharge was calculated from the number of blocks released by the ice block feeder over a given time interval when $Q_i < BV_s$.

RESULTS

A summary of the experimental runs is presented in Appendix A for the block size distributions (n_2:n_1) of 1:1, 1:2.3, 1:4, 1:6 and 1:9. Data for the uniform block experiments and for a majority of the 1:2.3 distribution may be found in Calkins and Ashton.[3]

Many factors affect the arching or nonarching of fragmented ice. For example, if we consider only uniform ice floes passing through an opening in an ice boom, the independent variables could be

$$A = f(Q_i, \bar{a}, b, B, V_s, t, h, T, g, \rho, \rho', V_g) \qquad (1)$$

where A = a discriminant function distinguishing arching events from nonarching events

$\bar{a}$ = block dimension characteristics

B = width of upstream channel

t = thickness of ice

h = depth of flow

T = interparticle shearing coefficient

g = acceleration of gravity

ρ = density of water

ρ' = density of ice

V_g = velocity through gap opening.

A possible nondimensional grouping is

$$A = f\left(\frac{Q_i}{V_s B}, \frac{Q_i}{V_s b}, \frac{b}{B}, \frac{\bar{a}}{b}, \frac{V_g}{V_s}, \frac{\rho'}{\rho}, \frac{T\bar{a}^2 g}{V^2 t}, \frac{t}{h}, \frac{V^2}{gt}\right)$$

In the present experiments, ρ'/ρ and t/h were constant. No attempt was made to assess T, and the velocity was maintained sufficiently low that Froude-type effects, which would be embodied in the V^2/gt term, were considered to be unimportant. Further, since the boom was a surface barrier with discrete elements and a small surface opening between the elements, the ratio of V_g/V_s is expected to vary little, which leads to

$$\frac{\bar{a}}{b} = F\left(\frac{b}{B}, \frac{Q_i}{V_s B}\right). \qquad (2)$$

These nondimensional groups are similar to those proposed by Calkins and Ashton.[3]

The characteristic length for the side dimension of a block in a mixture of two sizes of blocks is defined as

$$\bar{a} = \frac{n_1 a_1 + n_2 a_2}{n_1 + n_2} \qquad (3)$$

where n_1 and n_2 are the numbers of blocks with side dimensions a_1 and a_2, respectively. Calculation of the characteristic block dimension could have been based on the relative total areas of the two sizes of blocks, but the difference in values between the two methods did not seem significant, and was generally less than 5%. It was therefore decided to use the weighted arithmetic mean of the block side dimensions as the parameter for the characteristic block dimension.

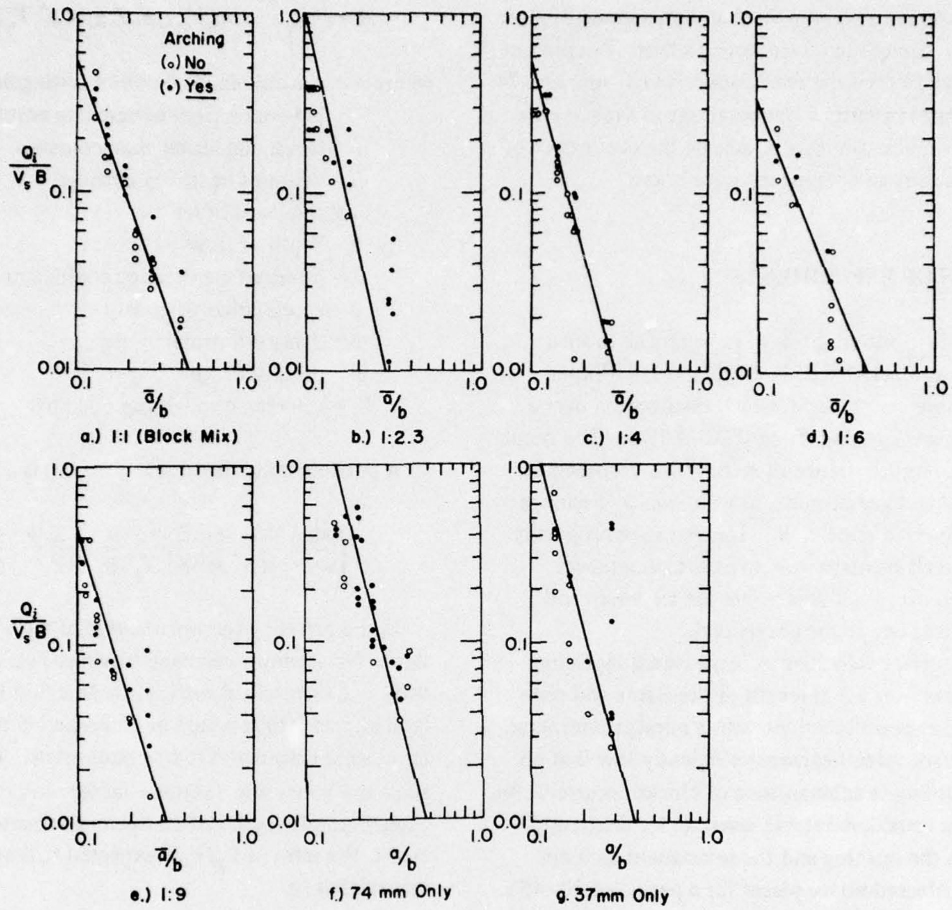

Figure 4. Separation of arching and nonarching events for each block mixture variation.

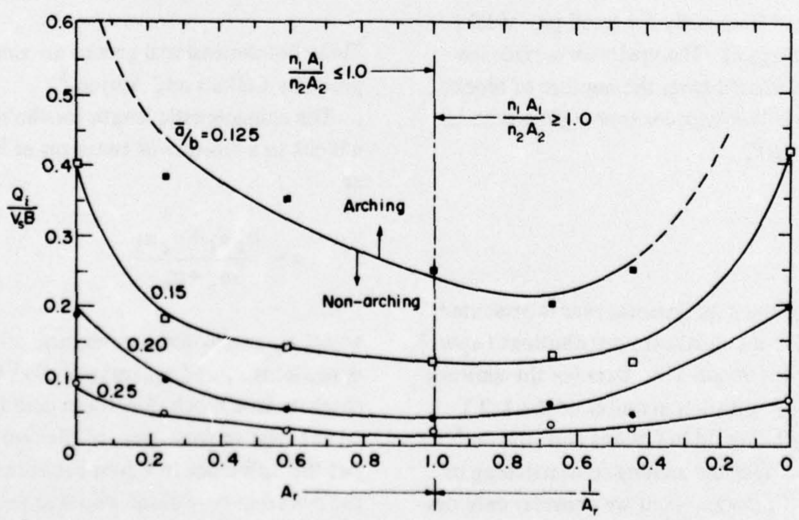

Figure 5. Separation of arching and nonarching condition for all experiments. Each line of $\bar{a}/b$ = constant best distinguishes between arching and nonarching for values of A_r and Q_i/V_sB.

Table I. Discriminate regression analysis.

Data set	Block mix	Intercept α	Slope $-\beta$	Remarks
1	37-mm blocks	2.60×10^{-4}	3.91599	Uniform block
2	74-mm blocks	3.52×10^{-4}	4.29484	block size
3	1:1	1.16×10^{-3}	2.67254	
4	1:2.3	4.00×10^{-5}	4.42311	
5	1:4	1.29×10^{-4}	3.61868	Block mix ratio
6*	1:6	1.17×10^{-3}	2.44544	n_{74}/n_{37}
7	1:9	2.44×10^{-4}	3.22169	
8	(2+3)	1.75×10^{-4}	4.52885	
9	(8+3)	2.80×10^{-4}	3.97641	Combination of
10	(4+5)	1.10×10^{-4}	3.80701	data sets
11†	(6+7)	5.90×10^{-4}	2.79337	
12*	(6+7)	2.50×10^{-4}	3.28376	

* 4 data points were omitted because arching could not be achieved at any ice discharge rate when $\bar{a}/b$ was less than 0.12.

† All data points included from (6).

The data obtained from the experiments for all block distributions are shown in Figure 4 with the line of best discrimination separating the nonarching and arching events. The threshold of arching can be represented by the power function:

$$\frac{Q_i}{V_s B} = \alpha \left(\frac{\bar{a}}{b}\right)^{\beta} \tag{4}$$

where α is the intercept and β the slope of the discrimination line. To distinguish between the occurrence and nonoccurrence of arching, a discriminate analysis was performed based on a technique of multiple linear regression.[4] Table I is a list of the intercepts and slopes for all experimental groups. No trend is apparent except that the slopes of the equations appear to be within a range of -2.5 to -4.5, with the intercepts at peak values for the minimum values of the slopes.

The curves in Figure 5 distinguish between the arching and nonarching events for given values of $\bar{a}/b$. The points on which these curves are based were not calculated from the discriminate equations for each block (n_2/n_1) ratio, but were based on the experimental data surrounding each value of $\bar{a}/b$. The term Q_i/V_sB represents the upstream ice discharge normalized by the water surface discharge required to yield ice concentrations from 0 to 1.0. A_r, the block area ratio, is a measure of the areal distribution of the two block sizes, such that

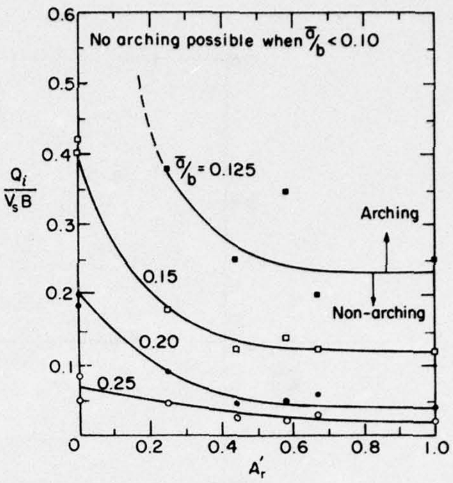

Figure 6. Composite of all arching and nonarching events. Each line of $\bar{a}/b$ = constant best separates the arching and nonarching condition for given values of ice concentration (Q_i/V_sB) and area block mixture (A'_r).

$$A_r = \frac{n_1 A_1}{n_2 A_2} \tag{5}$$

where n_1 and A_1 are the number and area of small blocks, respectively, and n_2 and A_2 are the number and area of the large blocks. To avoid the condition of A_r approaching infinity when the total area of the small blocks exceeds the area of the large blocks, the reciprocal $1/A_r$ is plotted when the block area ratio A_r exceeds 1.0 (1:4 block ratio).

The curves in Figure 5 are nearly symmetrical about the line $A_r = 1.0$, and thus the hypothesis previously set forth appears to be correct; that is, arching of ice floes occurs at minimum ice concentration when the ratio of block areas (A_r) is close to unity. If A'_r is defined with the conditions that $A'_r = A_r$ for $A_r < 1.0$ and $A'_r = 1/A_r$ for $A_r > 1.0$, then A'_r is always less than or equal to 1.0 and the data from Figure 5 can be transposed to reflect a composite graph as shown in Figure 6. Relatively smooth curves can be fitted through the data for the values of A'_r.

DISCUSSION OF RESULTS

A basic assumption has been made concerning the experimental work. It assumes that as long as the flow conditions are stable and no underturning of individual

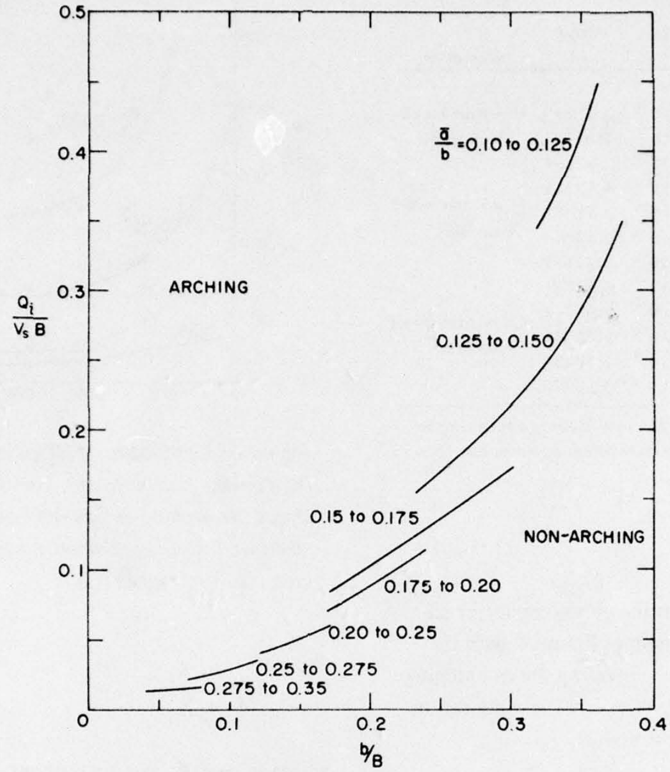

Figure 7. Effect of the ratio of gap width to flume width (b/β) on the arching events for a range of $\bar{a}/b$ values.

ice blocks occurs (i.e. the critical Froude number based on ice block thickness is not exceeded), the critical ice discharge resulting in arching of individual ice floes is independent of the flow velocity up to the critical flow velocity (or critical Froude number) that causes underturning of individual floes. This assumption is considered valid, and it has been verified by recent experiments conducted by Tatinclaux et al.[5]

No theoretical significance is attached to the form of eq 4, which discriminates arching and nonarching events, except for the dimensional analysis that suggests a functional relationship between the grouping of these variables. To answer the objective of this study (i.e. "Will a mixture of ice pieces nonuniform in size arch across an opening in an ice boom at a lower ice discharge than ice floes whose sizes are uniform?"), the data presented in Figure 4 are analyzed according to the areal distribution of the two component block sizes as shown in Figure 6.

The distinction between arching and nonarching conditions for two sizes of fragmented ice floes can be based on the total component areas of the two sizes, with the size having the greatest areal proportion being the critical factor. When the two component areas are equal ($A'_r = 1.0$), the concentration of floes upstream necessary for arching to occur is minimal and remains relatively constant until approximately $A'_r = 0.5$. For smaller values of A'_r, the concentration necessary for arching increases noticeably toward the single-sized block ($A'_r = 0$ is approached). The rate of change of Q_i/V_sB increases dramatically as the value of $\bar{a}/b$ varies from 0.25 to 0.10.

Arching of fragmented floes becomes more difficult when the ratio $\bar{a}/b$ approaches 0.10 and appears from the limited data obtained in this study to be independent of b/B. It was not possible to sustain an arch when $\bar{a}/b <$ 0.10, regardless of the upstream ice discharge. In several cases, the fragmented cover would accumulate in the

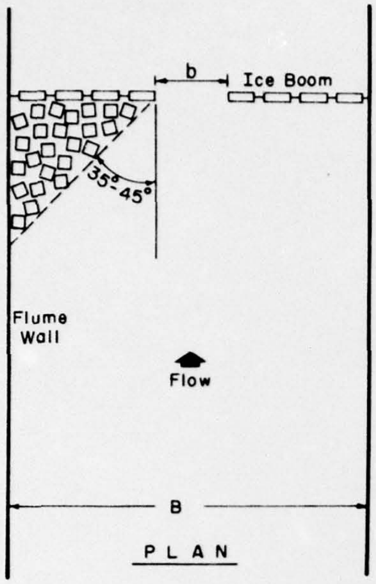

Figure 8. Initial retention area of ice floes in the eddy zones behind a surface barrier.

upstream direction, with a constant discharge of ice through the opening in the boom but without arching occurring.

To evaluate the influence of the flume width on the experimental results, Figure 7 was prepared from the available data for the range of $\bar{a}/b$ values from 0.10–0.35. Each curve separates the arching and nonarching events for the range of $\bar{a}/b$ values and the given b/B ratios. The experiments were not designed to fully study the effect of b/B, and extrapolation of the family of curves in Figure 7 should be done with caution. The influence of b/B could be studied in more detail if false walls were adapted to the flume.

The physical processes observed in arching of fragmented floes in an open channel at a surface barrier opening can be divided into two classes, depending on the ice discharge in the channel. The first class occurred when floes at low surface concentration approached the surface barrier and accumulated in the eddy zones on the upstream side of the barrier, leaving a funnel-shaped opening leading to the gap in the boom (Fig. 8). When the upstream discharge was less than the maximum theoretical nonarching ice discharge and when $\bar{a}/b > 0.30$, the floes accumulated in the eddy zones and then a group of them tended to rotate toward the opening. This often caused an arch to form because of the resulting localized high concentration near the gap. These conditions were treated as arching occurrences. A parameter not measured, but which should be included in subsequent tests, is the time to form an arch at the gap opening. With information on the time necessary for arching and the corresponding block concentration, a statistical analysis could estimate the probability of a distribution arriving at the opening over a given time interval.

The second class of arch formation processes resulted when a high concentration of ice was released such that the maximum ice discharge through the gap opening was exceeded and a progression of the cover upstream would take place with arching of floes at the gap opening. However, when the ratio $\bar{a}/b <$ 0.12, it was possible to have an upstream progression of the cover and still discharge ice through the opening without creating an arch.

The use of polyethylene plastic as a model ice has disadvantages. The influence of the interparticle shearing and refreezing of ice floes cannot be evaluated, and the effects of surface tension on plastic and ice are different.

SUMMARY AND CONCLUSIONS

Arching of mixtures of two sizes of square model ice floes at an opening in an ice boom was examined, subject to the condition that surface water velocities were slower than the critical velocity for underturning or submerging individual ice pieces. Polyethylene blocks were used as the model ice and experiments were conducted in a laboratory flume.

The following results were found:

1. Arching phenomena at the gap opening were independent of the channel velocity up to the critical velocity for underturning. (This result has also been recently verified by Tatinclaux et al.[5])

2. Uniform (single-sized) floes required a higher concentration to initiate arching than nonuniform mixtures of pieces.

3. When the total areas of two sizes of components were equal, or when one was at least 60% of the other, the ice concentration was at the minimum necessary for arching of the fragmented pieces. This applied for the range of $\bar{a}/b$ values from 0.10 to 0.25.

4. When $\bar{a}/b$ values increased to 0.25 the ice concentration necessary to initiate arching was unaffected by variations in the component areas (see Fig. 6).

5. The effect of the flume width B on the arching process could not be totally established with regard to the ratio b/B. The limited amount of data and apparent nonlinearity do not allow for easy interpretation (see Fig. 7). Further experimentation is needed to properly account for the influence of flume width.

6. The validity of using plastic material as a model substitute for real ice is not clear. Tatinclaux et al.[5] suggest that real ice behaves with no noticeable differences for the smaller size floes, but for the larger floes (74 mm) the real ice requires a higher concentration for arching. No clear explanations are yet available concerning this unexpected difference, as it was originally conceived that the plastic floes would require higher concentrations to initiate arching. The effect of surface tension may be important. Also, the choice of square-shaped model pieces was made for convenience in handling and discharging into the flume and additional experiments with other shapes are in order.

7. Arching of floes could not be achieved for values of $\bar{a}/b < 0.10$.

LITERATURE CITED

1. Boulanger, F., E. Dumalo, D. Le Van and L. Racicot (1975) Ice control study, Lake St. Francis-Beauharnois Canal. *Third International Symposium on Ice Problems*, International Association for Hydraulic Research.
2. Calkins, D.J. (1975) A research hydraulic flume for modeling drifting snow: Design, construction and calibration. U.S. Army Cold Regions Research and Engineering Laboratory Technical Report 251.
3. Calkins, D.J. and G.D. Ashton (1975) Arching of fragmented ice covers. *Canadian Journal of Civil Engineering*, vol. 2, no. 4, p. 392-399. (Also CRREL Special Report 222.)
4. Panofsky, H.A. and G.W. Brier (1968) *Some applications of statistics to meteorology*. University Park: Pennsylvania State University, 224 p.
5. Tatinclaux, J.C., C.L. Lee, T.P. Wang, T. Nakato and J.F. Kennedy (1976) A laboratory investigation of the mechanics and hydraulics of river ice jams. Iowa Institute of Hydraulic Research, The University of Iowa, IIHR Report No. 186, also CRREL Report (in press).

APPENDIX A: SUMMARY OF ARCHING EXPERIMENTS – MIXED BLOCK SERIES

(B = 0.925 m, t = 6.4 mm.)

b (m)	D (m)	V_s (m/s)	Blocks released / time (s)	Q_i (m^2/s)	$\bar{a}$	$\bar{a}/b$	Q_i/VB	b/B	Stable arch
Block mix ratio 1:1									
0.160	0.575	0.080	68/90	0.00259	0.056	0.350	0.035	0.17	Yes
0.160	0.575	0.080	196/467	0.00144	0.056	0.350	0.019	0.17	No
0.160	0.575	0.080	280/780	0.00123	0.056	0.350	0.017	0.17	Yes
0.205	0.575	0.080	208/136	0.00523	0.056	0.273	0.071	0.22	Yes
0.205	0.575	0.080	280/334	0.00286	0.056	0.273	0.039	0.22	No
0.205	0.575	0.076	280/489	0.00196	0.056	0.273	0.028	0.22	No
0.205	0.575	0.076	280/330	0.0029	0.056	0.273	0.041	0.22	Yes
0.205	0.575	0.076	280/427	0.00224	0.056	0.273	0.032	0.22	No
0.205	0.575	0.076	280/376	0.00255	0.056	0.273	0.036	0.22	Yes
0.250	0.575	0.076	280/330	0.00288	0.056	0.224	0.041	0.27	No
0.250	0.575	0.076	280/230	0.00417	0.056	0.224	0.059	0.27	Yes
0.250	0.575	0.076	280/286	0.00335	0.056	0.224	0.048	0.27	No
0.250	0.575	0.076	280/233	0.00411	0.056	0.224	0.058	0.27	Yes
0.318	0.575	0.076	280/145	0.00661	0.056	0.180	0.094	0.34	No
0.318	0.575	0.076	280/111	0.00863	0.056	0.180	0.123	0.34	Yes
0.318	0.575	0.076	420/147	0.00978	0.056	0.180	0.139	0.34	Yes
0.318	0.575	0.076	420/207	0.00694	0.056	0.180	0.099	0.34	No
0.365	0.575	0.076	420/86	0.01671	0.056	0.153	0.238	0.40	Yes
0.365	0.575	0.076	420/99	0.01452	0.056	0.153	0.206	0.40	Yes
0.365	0.575	0.080	420/106	0.01356	0.056	0.153	0.183	0.40	Yes
0.365	0.575	0.080	420/128	0.0112	0.056	0.153	0.151	0.40	Partial
0.365	0.575	0.080	420/151	0.0095	0.056	0.153	0.128	0.40	No
0.443	0.575	0.080	420/76	0.01879	0.056	0.126	0.254	0.48	No
0.443	0.575	0.080	420/60	0.02396	0.056	0.126	0.324	0.48	Yes
0.443	0.575	0.080	420/53	0.02712	0.056	0.126	0.367	0.48	Yes
Block mix ratio 1:2.3									
0.160	0.575	0.080	308/420	0.00184	0.048	0.30	0.025	0.17	Yes
0.160	0.575	0.080	322/440	0.00178	0.048	0.30	0.024	0.17	Yes
0.160	0.575	0.080	105/300	0.0008	0.048	0.30	0.011	0.17	Yes
Block mix ratio 1:4									
0.162	0.570	0.077	180/360	0.00110	0.044	0.27	0.015	0.18	Yes
0.162	0.570	0.077	360/720	0.00110	0.044	0.27	0.015	0.18	Yes
0.162	0.570	0.077	250/600	0.00091	0.044	0.27	0.013	0.18	No

b (m)	D (m)	V_s (m/s)	Blocks released / time (s)	Q_i (m^2/s)	$\bar{a}$	$\bar{a}/b$	Q_i/VB	b/B	Stable arch
Block mix ratio 1:4 (cont'd)									
0.162	0.570	0.077	120/192	0.00137	0.044	0.27	0.019	0.18	Yes
0.162	0.570	0.077	240/384	0.00137	0.044	0.27	0.019	0.18	No
0.162	0.570	0.077	240/384	0.00137	0.044	0.27	0.019	0.18	Yes
0.275	0.57	0.077	180/72	0.0055	0.044	0.16	0.077	0.30	No
0.275	0.57	0.077	260/104	0.0055	0.044	0.16	0.077	0.30	No
0.275	0.57	0.077	260/78	0.0073	0.044	0.16	0.102	0.30	No
0.252	0.57	0.077	260/78	0.0073	0.044	0.175	0.102	0.27	Yes
0.252	0.57	0.077	260/104	0.0055	0.044	0.175	0.064	0.27	Yes
0.252	0.57	0.077	260/130	0.0044	0.044	0.175	0.062	0.27	No
0.252	0.57	0.077	260/130	0.0044	0.044	0.175	0.062	0.27	No
0.252	0.583	0.060	240/96	0.0055	0.044	0.175	0.099	0.27	Yes
0.315	0.585	0.060	360/108	0.0073	0.044	0.14	0.132	0.34	No
0.315	0.585	0.060	360/86.4	0.0091	0.044	0.14	0.164	0.34	Yes
0.315	0.585	0.064	484/115.2	0.0091	0.044	0.14	0.154	0.34	No
0.315	0.58	0.064	FEED	SYSTEM	JAMMED				
0.315	0.58	0.064	480/96	0.0110	0.044	0.14	0.186	0.34	Yes
0.315	0.57	0.082	480/115	0.0091	0.044	0.14	0.120	0.34	No
0.315	0.57	0.082	480/96	0.0110	0.044	0.14	0.145	0.34	Yes
0.440	0.57	0.082	480/48	0.0219	0.044	0.10	0.289	0.48	No
0.400	0.57	0.082	480/48	0.0219	0.044	0.11	0.289	0.43	No
0.36	0.57	0.079	500/50	0.0219	0.044	0.12	0.300	0.39	No
0.36	0.57	0.079	740/61	0.0266	0.044	0.12	0.364	0.39	Yes
0.36	0.57	0.079	740/61	0.0266	0.044	0.12	0.364	0.39	Yes
Block mix ratio 1:6									
0.162	0.570	0.077	197/390	0.0010	0.042	0.26	0.014	0.18	No
0.162	0.570	0.077	224/384	0.00110	0.042	0.26	0.015	0.18	No
0.162	0.570	0.077	224/320	0.0014	0.042	0.26	0.020	0.18	No
0.162	0.570	0.077	168/240	0.0014	0.042	0.26	0.020	0.18	No
0.162	0.570	0.077	168/192	0.0017	0.042	0.26	0.024	0.18	No
0.162	0.570	0.077	168/144	0.0023	0.042	0.26	0.032	0.18	Yes
0.162	0.570	0.077	168/96	0.0034	0.042	0.26	0.048	0.18	Yes
0.162	0.570	0.077	168/96	0.0034	0.042	0.26	0.048	0.18	No
0.162	0.570	0.077	168/96	0.0034	0.042	0.26	0.048	0.18	Yes
0.252	0.583	0.060	336/96	0.0068	0.042	0.175	0.123	0.27	No
0.252	0.583	0.060	336/96	0.0068	0.042	0.175	0.123	0.27	No
0.252	0.580	0.060	336/72	0.0091	0.042	0.17	0.164	0.27	Yes
0.252	0.580	0.060	336/72	0.0091	0.042	0.17	0.164	0.27	Yes
0.315	0.58	0.064	604/96	0.0137	0.042	0.13	0.231	0.34	No
0.315	0.57	0.082	672/96	0.0137	0.042	0.13	0.181	0.34	Yes
0.315	0.57	0.082	672/96	0.0137	0.042	0.13	0.181	0.34	Yes
0.315	0.57	0.082	672/115	0.0114	0.042	0.13	0.150	0.34	Yes
0.315	0.57	0.082	672/144	0.0091	0.042	0.13	0.120	0.34	No
0.315	0.57	0.082	672/144	0.0091	0.042	0.13	0.120	0.34	No
0.400	0.57	0.082	672/48	0.0274	0.042	0.11	0.361	0.43	No
0.36	0.57	0.081	700/50	0.0274	0.042	0.117	0.366	0.39	No
0.36	0.57	0.081	700/50	0.0274	0.042	0.117	0.366	0.39	No
0.252	0.57	0.081	700/150	0.0091	0.042	0.167	0.121	0.27	Yes
0.252	0.57	0.081	700/210	0.0065	0.042	0.167	0.087	0.27	Yes
0.252	0.57	0.081	700/206	0.0066	0.042	0.167	0.087	0.27	No
0.400	0.57	0.081	700/39	0.0351	0.042	0.105	0.468	0.43	No

b (m)	D (m)	V_s (m/s)	Blocks released / time (s)	Q_i (m^2/s)	$\bar{a}$	$\bar{a}/b$	Q_i/VB	b/B	Stable arch
Block mix ratio 1:9									
0.544	0.575	0.080	420/42	0.03422	0.056	0.126	0.462	0.59	No
0.160	0.575	0.080	350/91	0.00685	0.041	0.256	0.093	0.17	Yes
0.160	0.575	0.080	350/149	0.00418	0.041	0.256	0.056	0.17	Yes
0.160	0.575	0.080	350/600	0.00104	0.041	0.256	0.014	0.17	No
0.160	0.575	0.080	600/360	0.00297	0.041	0.256	0.040	0.17	Yes
0.160	0.575	0.080	600/532	0.00201	0.041	0.256	0.027	0.17	Yes
0.205	0.575	0.080	700/446	0.00279	0.041	0.20	0.038	0.22	No
0.205	0.575	0.080	600/259	0.00412	0.041	0.20	0.056	0.22	Yes
0.205	0.575	0.080	450/141	0.00568	0.041	0.20	0.077	0.22	Yes
0.205	0.575	0.080	450/232	0.00345	0.041	0.20	0.047	0.22	Yes
0.250	0.575	0.080	700/237	0.00526	0.041	0.16	0.071	0.27	Yes
0.250	0.575	0.080	700/211	0.0059	0.041	0.160	0.080	0.27	Yes
0.250	0.575	0.080	700/279	0.00477	0.041	0.160	0.065	0.27	No
0.250	0.575	0.080	700/247	0.00504	0.041	0.160	0.068	0.27	No
0.315	0.575	0.080	700/210	0.00593	0.041	0.130	0.080	0.34	No
0.315	0.575	0.080	700/146	0.00853	0.041	0.130	0.115	0.34	No
0.315	0.575	0.080	700/134	0.0093	0.041	0.130	0.126	0.34	Yes
0.315	0.575	0.080	700/150	0.00831	0.041	0.130	0.112	0.34	No
0.315	0.575	0.080	700/125	0.00997	0.041	0.130	0.135	0.34	No
0.315	0.575	0.080	700/116	0.01074	0.041	0.130	0.145	0.34	No
0.315	0.575	0.080	700/95	0.01311	0.041	0.130	0.177	0.34	Yes
0.360	0.575	0.080	700/94	0.01325	0.041	0.110	0.179	0.39	No
0.360	0.575	0.080	700/78	0.01597	0.041	0.110	0.216	0.39	No
0.360	0.575	0.080	700/59	0.02112	0.041	0.110	0.285	0.39	Yes
0.250	0.575	0.080	700/144	0.00865	0.041	0.160	0.117	0.27	Yes
0.36	0.575	0.080	700/44	0.02831	0.041	0.110	0.384	0.39	Yes
0.36	0.575	0.080	700/44	0.02831	0.041	0.110	0.384	0.39	No
Block mix ratio 0.074									
0.365	0.575	0.080	210/79	0.01456	0.074	0.20	0.197	0.40	No